

# Pulsed Gamma-Ray-Burst Afterglows

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## ABSTRACT

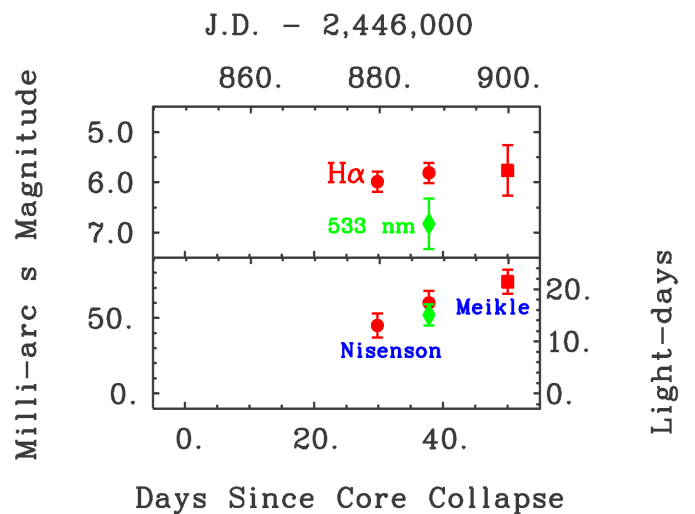
The bipolarity of Supernova 1987A can be understood in terms of its very early light curve as observed from the CTIO 0.4-m telescope, as well as the IUE FES, and the slightly later speckle observations of the “Mystery Spot” by two groups. These observations imply a highly directional beam of light and jet of particles, with initial collimation factors in excess of  $10^4$ , velocities in excess of 0.95 c, as an impulsive event involving up to  $10^{-5} M_{\odot}$ , which interacts with circumstellar material. The jet and beam coincide with the  $194^{\circ}$  angle of the bipolarity on the sky, and are oriented at  $75^{\circ}$  to the line of sight to the Earth. By day 30 the collimation of the jet decreases, and its velocity declines to  $\sim 0.5$  c. These observations and the resulting kinematic solution can be understood in terms of pulsar emission from polarization currents, induced by the periodically modulated electromagnetic field beyond the pulsar light cylinder, which are thus modulated at up to many times the speed of light. With plasma available at many times the light cylinder radius, as would be the case for a spinning neutron star formed at the center of its progenitor, pulsed emission is directed close to the rotation axis, eviscerating this progenitor, and continuing for months to years, until very little circumpulsar material remains. There is no reason to suggest that this evisceration mechanism is not universally applicable to all SNe with gaseous remnants remaining. Calculations of this mechanism are orders of magnitude more difficult than previously imagined for any pulsar interaction with its remnant progenitor. This model provides a candidate for the central engine of the gamma-ray burst (GRB) mechanism, both long and short, and predicts that GRB afterglows are the *pulsed* optical/near infrared emission associated with these newly-born neutron stars. It also provides a mechanism to accelerate electrons and positrons to ultrarelativistic energies, possibly accounting for the results from PAMELA and ATIC, and the WMAP haze. It is also possible, within the context of this model, that the prompt emission from the gamma-ray burst itself may result from a white dwarf near Chandrasekhar mass rotating with its minimum period near 2 s, rather than from the more rapidly rotating neutron star formed from its subsequent collapse. We note that the bipolarity, enforced on early SN remnants by their embedded pulsars, i.e., very fast axial ejection features within expanding toroids, may complicate their utility, as standard candles, to cosmological interpretation.

**Key words.** Acceleration of particles – Gamma rays: bursts – pulsars: general – Stars: neutron – supernovae: general – supernovae: individual: SN 1987A

## 1. Introduction

Supernova 1987A has provided astronomers with a wealth of data, some of which has not even now, 22 years after the event, been satisfactorily accounted for by any model. One of the most remarkable features in the early study of SN 1987A was the “Mystery Spot”, with a thermal energy of  $10^{49}$  ergs, observed 50 days after the core-collapse event (Meikle et al. 1987; Nisenson et al. 1987; Nisenson & Papaliolios 1999), and separated from the SN photosphere “proper” by  $0.060 \pm 0.008$  arc s at day 38 (Fig. 1), with about 3% of this energy eventually radiated in the optical band. The possibility that the enormous energy implied for the Mystery Spot might somehow link it to gamma-ray bursts (GRBs) attracted little serious consideration at the time, or even since, beyond a very astute few (Rees 1987; Piran & Nakamura 1987; Cen 1999). The Mystery Spot was also observed at separations of  $0.045 \pm 0.008$  arc s on day 30, and  $0.074 \pm 0.008$  arc s on day 50, but always at an angle of  $194^{\circ}$ , consistent with the southern (and approaching) extension of the bipolarity (Wang et al. 2002). The Mystery Spot offsets from SN 1987A imply a minimum projected separation of  $\sim 10$  light-days (ft-d).

There is also a wealth of photometric and spectroscopic data from even earlier stages of SN 1987A, in particular photometry data from the Cerro Tololo Inter-American Observatory (CTIO)



**Fig. 1.** Measurements of displacement (lower) and observed magnitude (upper) of the “Mystery Spot” from SN 1987A, at  $H_{\alpha}$  and 533 nm, vs time, from Meikle et al. (1987), Nisenson et al. (1987), and Nisenson and Papaliolios (1999).

0.4-m telescope (Hamuy & Suntzeff 1990), and the Fine Error Sensor (FES) of the International Ultraviolet Explorer (IUE – Wamsteker et al. 1987), and spectroscopic data from Danziger et al. (1987), and Menzies et al. (1987), among others. Short timescale structure ( $\leq 1$  d) in this data, following finite delays ( $\sim 10$  d) after SN 1987A core-collapse, implies at least one beam of light and jet particles which are highly collimated ( $>10^4$ ), interacting with circumstellar material.

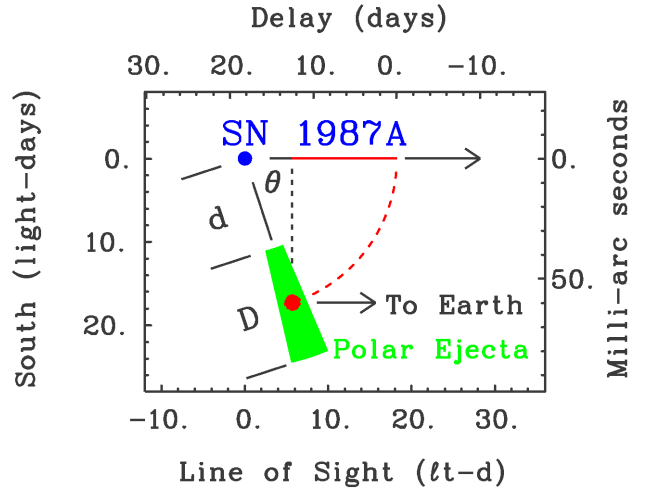
GRBs, particularly long, soft GRBs ( $\ell$ GRBs), appear to be the most luminous objects in the Universe, occurring at the SN rate of one per second (assuming a collimation factor near  $10^5$ ) yet we still know very little about them (see, e.g., Mészáros 2006 and references therein). Although some have been found to be associated with SNe, others, mostly those with slightly harder spectra and lasting only  $\sim 1$  second, (sGRBs), produce *only* “afterglows” (if that), sometimes extending down to radio wavelengths. A large number of models have been put forth to explain GRBs, including neutron star-neutron star mergers for sGRBs, and exotic objects such as “collapsars” (MacFadyen & Woosley 1999) for  $\ell$ GRBs. The prime physical motivation for these is the enormous energy of up to  $10^{54}$  ergs implied for an isotropic source. However, given that the data from SN 1987A presented herein support a beam/jet collimation factor  $>10^4$  in producing its early light curve by interaction with more-or-less stationary circumstellar material (see below), there may be no need for such a high energy.

This work argues that polarization currents, induced beyond the light cylinders of, and by the rotating magnetic fields from, newly-formed pulsars embedded within their stellar remnants (Kuo-Petravic et al. 1974; Braje & Romani 2001), can account for the bipolarity of SN 1987A (Ardavan 1994,8; Ardavan et al. 2008). This model of emission from superluminally induced polarization currents (SLIP) provides a mechanism for generating a pulsed beam on the surface of a cone, whose half angle (and angle from the pulsar axis of rotation) is given by,

$$\theta_V = \sin^{-1} c/v, \quad (1)$$

for astronomical distances. Here  $c$  is the speed of light, and  $v > c$  is the speed at which the polarization currents are updated, i.e.,  $v = \omega R$ , where  $\omega$  is the pulsar rotation frequency, in radians  $s^{-1}$ ,  $R > R_{LC}$  is the distance of the polarization current from the pulsar, projected onto the rotational equatorial plane, and  $R_{LC}$  is the light cylinder radius ( $\omega R_{LC} = c$ ). The power emitted rises steeply with  $v$  (Ardavan et al. 2004), and this beam, in turn acting as a phased array, accelerates matter into a conical jet, centered about the axis of rotation.

In the rest of this paper, Sect. 2 includes a quantitative discussion of the SN 1987A early luminosity history and motivations for why a later, quasi-steady, less collimated, as well as a prompt, highly collimated, injection event, is also needed. Then Sect. 3 estimates the kinematics and a working geometry for the 1987A beam/jet and Mystery Spot. We explore the implications of the kinetics and observations on the process which gave rise to SN 1987A. Section 4 relates the SN 1987A beam/jet process to GRBs and germinates the idea that they and their afterglows are highly pulsed, while Sect. 5 relates the process to Type Ia/c SNe. Section 6 extends the discussion of implications of the SN 1987A process to Type II SNe, the importance of plasma to weakly magnetized pulsars, and its role in the history of observations of SN 1987A, as well as the consequences of the motion of the Mystery Spot, and of the high kinetic energy of particles in the SN 1987A jet(s). Finally, Section 7 concludes.



**Fig. 2.** The geometry of the “Mystery Spot,” (red dot) polar ejecta, associated beam/jet, and direct line of sight from SN 1987A to the Earth.

## 2. The Early Luminosity History of SN 1987A

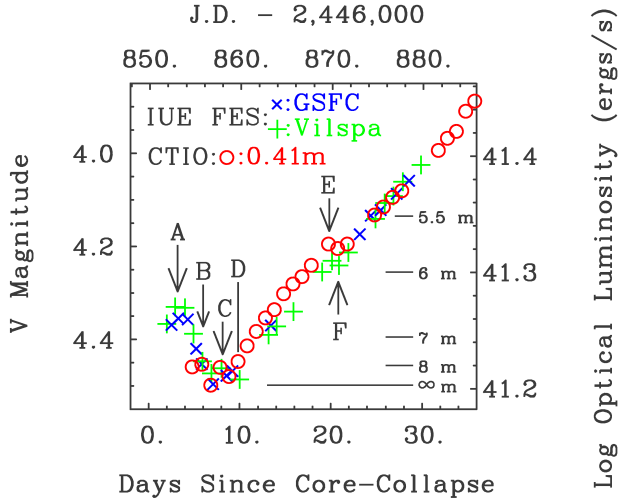
Table 1 gives an event history for SN 1987A and its progenitor system. An approximate geometry for SN 1987A and a Mystery Spot located within circumstellar material (in this case, polar ejecta), is given in Fig. 2, while the early luminosity histories of SN 1987A from CTIO, and the Fine Error Sensor (FES) of the IUE, are both plotted in Fig. 3.<sup>1</sup>

**Table 1.** SN 1987A Event Log

Time t	Event
-20,000 years	Rings formed
$\sim(-2,000?)$ years	Polar, or near-polar ejection
0 (= UT 1987, Feb. 23.316)	Core-collapse of SN 1987A
$0 < t < 2$ days	UV flash from SN 1987A
$2 < t < 4$ days	Emergence of luminous jet
$4 < t < 7$ days	Cooling/spreading of jet
7.8 days	UV flash hits polar ejecta
8.26 days	Jet impacts polar ejecta (PE)
19.8 days	Pulsations clear through PE
20.8 days	Jet particles clear through PE
30 days	“Mystery spot” at 45 mas
38 days	“Mystery spot” at 60 mas
50 days	“Mystery spot” at 74 mas

Following the drop from the initial flash, the luminosity rises again to a maximum (‘A’ in Fig. 3 and Fig. 4, top) of magnitude 4.35 at day 3.0, roughly corresponding to  $2.7 \times 10^{41}$  ergs  $s^{-1}$  and interpretable as a luminous jet emerging from cooler, roughly cylindrical outer layers which initially shrouded it. This declines to magnitude 4.48 around day 7.0 (‘B’, Fig. 4, middle), interpretable as free-free cooling, or the loss of the ability to cool, as the jet becomes more diffuse. The next observable event should be the scattering/reprocessing of the initial UV flash in the polar

<sup>1</sup> The CTIO V band center occurs at 5,500 Å, as opposed to 5,100 Å for the FES, and in consequence, the FES magnitudes have been diminished by 0.075 in Fig. 3 to account for the resulting luminosity offset, and the CTIO times (Hamuy & Suntzeff 1990) are too early by 1 day, and have been corrected in this work.



**Fig. 3.** The very early luminosity history of SN 1987A as observed with the Fine Error Sensor of IUE and the 0.41-m at CTIO. Data points taken at Goddard Space Flight Center by Sonneborn & Kirshner, and at the Villafranca Station in Madrid, are marked (see Sect. 2).

ejecta at day  $\sim 8$ , and indeed ‘C’ (Fig. 4, bottom) shows  $\sim 2 \times 10^{39}$  ergs  $s^{-1}$  in the optical for a day at day 7.8, and a decline *consistent with the flash* after that, indicating that no significant smearing over time had occurred in this interaction. The 8 day delay to this first event implies a collimation factor  $> 10^4$  for this part of the UV flash.

A linear ramp in luminosity, visible by day 9.8 (‘D’ in Fig. 3 and Fig. 5, top), indicates particles from the jet penetrating into the polar ejecta, with the fastest traveling at  $> 0.8 c$ , and, because of the sudden rise, a particle collimation factor  $> 10^4$  (see further below). Back-extrapolation of the three CTIO points just after day 8 intersects the day 7 minimum near day 8.26, which would indicate that particles exist in this jet with velocities up to  $0.95 c$ , and even higher if the true minimum flux is lower than the points at magnitude 4.48 ( $1.6 \times 10^{41}$  erg  $s^{-1}$ ) near day 7.

The ramp continues until after day 20, when a decrement of  $\sim 5 \times 10^{39}$  ergs  $s^{-1}$  appears in both data sets just after day 20 (‘F’ in Fig. 3, and Fig. 5, bottom). The CTIO point just before the decrement can be used as a rough upper limit for the Mystery Spot luminosity, and corresponds to an excess above the minimum (near day 7.0) of  $5 \times 10^{40}$  ergs  $s^{-1}$ , or magnitude 5.8, the same as that observed in  $H\alpha$  for the at days 30, 38, and 50, about 23% of the total optical flux of  $2.1 \times 10^{41}$  ergs  $s^{-1}$  at that time.

This decrement is preceded by a *spike* (‘E’ in Fig. 3, Fig. 5, middle, and Fig. 6, day 19.8) of up to  $10^{40}$  ergs  $s^{-1}$  in the CTIO data, with the unusual colors of B, R, and I, in ascending order, very close to the B and I bands speculated for the 2.14 ms signature observed from 1987A by Middleditch et al. (2000a,b – hereafter M00a,b), with an  $H\alpha$  enhancement. Spectra taken by Danziger et al. (1987), on UT 1987, March 15.08 (day 19.76), and Menzies et al. (1987), on March 14.820 (day 19.504), support these flux enhancements, including the  $H\alpha$ . The timing of this event, one day prior to the decrement, suggests that it is due to a photon stream, stripped of its UV component by absorption (the CTIO U point at day 19.8 was low, consistent with this interpretation), scattering into other directions, including the line of sight to the Earth, by what might have been a clumpy end to the circumstellar material. Pulsations were not

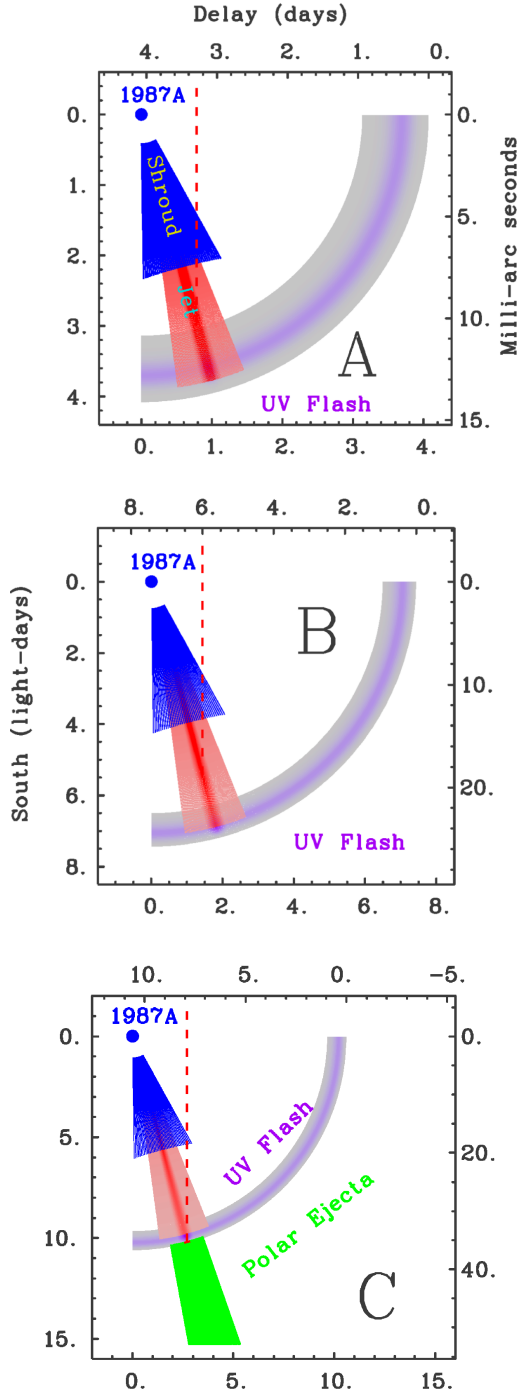
detected (R. N. Manchester, private communication), because of the oblique view, and the dimensions of the beam ( $\sim 1 \ell t$ -d).

For the geometry derived in Sect. 3 below, the one day delay implies at least the same maximum jet velocity ( $0.95 c$ ), supporting this interpretation, and giving us a rough isotropic lower limit estimate of the strength of the pulsations. Spectra taken just before day 5, showing an enhancement for wavelengths below  $5000 \text{ \AA}$ , explain the discrepancy between the CTIO and FES points at that time (Fig. 3).

In spite of the coincidence between the end magnitude of the linear ramp and that of the Mystery Spot, the two are probably not the same effect, as the offset of the Mystery Spot from SN 1987A was only  $0.045$  arc s even 10 days later at day 30 (Fig. 7), a location barely beyond where the ramp began, as is shown below, and there is no sign of elongation toward 1987A proper in Fig. 1 of Nisenson and Papaliolios (1999) or Fig. 2 of Nisenson et al. (1987). The Mystery Spot may develop as a plume within the polar ejecta, pushed by a less collimated,  $0.5 c$  pulsar wind, perhaps not unlike that observed from the Crab pulsar (Hester et al. 2002), after the passage of the initial, very fast, very collimated component of the jet. A beam only  $1 \ell t$ -d across at  $\sim 10 \ell t$ -d translates into plasma at  $\sim 20 R_{LC}$ . Alternately, the early light curve might be due to shallow penetration of a precessing jet into a varying entry point into the polar ejecta. However, the high density required to limit jet penetration comes with a higher opacity which would make the linear ramp hard to produce in this, the inner boundary of the approaching axial feature, and the requirement for a  $0.5 c$  mean motion of the Mystery Spot between days 30 and 38, slowing to  $0.35 c$  between days 38 and 50 (ostensibly due to swept up matter), would also be difficult to account for in these circumstances. On the other hand, the polar ejecta density can not be so low as to allow more than  $1 \ell t$ -d penetration by the enhanced UV flash, or the drop in luminosity from day 7.8 to day 8.8 would not be as big. If the jet penetration is deep, precession and/or changes in the plasma density beyond the pulsar light cylinder (Eqn. 1), may make its initial track, within the polar ejecta, helical, and this may assist the  $\sim 0.5 c$  wind in the creation of the plume which forms the Mystery Spot within three weeks of the initial jet penetration.

We will assume that the optical flux from the interaction between jet particles and the polar ejecta will not be significantly occulted in the ejecta itself in the direction to the Earth, otherwise again, the linear ramp would be difficult to produce. As we will find below that the axis of the SN 1987A bipolarity is  $\sim 30^\circ$  from the normal to the ring planes, the reason remaining a mystery even today, this is not necessarily a given. Proceeding nevertheless: by scaling homologously inward a factor of 10 from the equatorial ring density of  $10^4 \text{ cm}^{-3}$ , we arrive at a polar ejecta density estimate of  $\sim 10^7 \text{ cm}^{-3}$  – sufficient to stop the UV flash from penetrating  $> 1 \ell t$ -d.

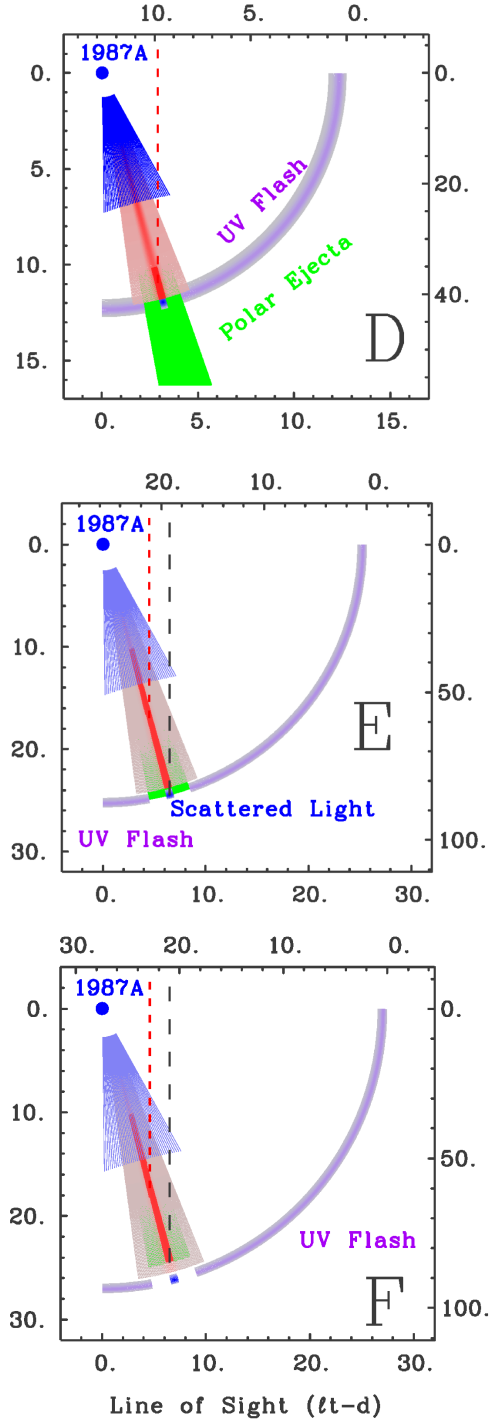
Assuming a polar ejecta depth,  $D$ , of  $\sim 10 \ell t$ -d, or  $2.6 \times 10^{16}$  cm, gives a total column of  $2.6 \times 10^{23} \text{ cm}^{-2}$ , enough to warrant some concern. However, only a fraction of the protons in the jet will scatter through the entire depth of the polar ejecta (the slight concave downward departure from linearity most apparent in the CTIO data, between days 9 and 20, may reflect this loss, and/or the density in the polar ejecta may decrease with distance). In addition, we will find that the angle,  $\theta$ , from our line of sight to the SN 1987A beam/jet, will be large in the self-consistent solution, justifying our assumption of visibility for the luminous column within the polar ejecta between days 9 and 20.



**Fig. 4.** The geometry of the 1987A glowing beam/jet, initially opaque shroud, and UV flash (which may have an enhanced beam of its own in the jet direction – here  $75^\circ$ , down and to the right). The maximum velocity of the jet/shroud is 0.95/0.55 c. The dashed line to the upper scale flags the center of the emerging jet at day 3.3 (top – A), and day 6 (middle – B), and the UV flash hitting the polar ejecta at day 7.8 (bottom – C).

### 3. The Geometry and Kinematics of the Beam/Jet

Using the constraints shown in Figs. 1 and 3, we can solve for the three geometric variables,  $d$ ,  $D$ , and  $\theta$ , diagrammed in Fig. 2,

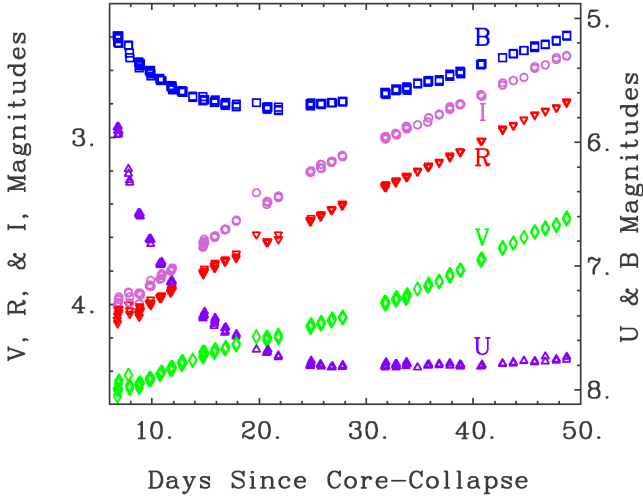


**Fig. 5.** (Top – D) The intense center ( $\sim 1^\circ$ ) of the jet begins to produce light as it penetrates into the polar ejecta, producing the jump in luminosity at day 9.8. (Middle – E) Particles in the jet continue to impact the polar ejecta (mostly hidden), extending the ramp in luminosity visible in Fig. 3 near day 20 (left dashed line to the top scale). (Right dashed line) Light from the filtered UV flash scatters in clumpy polar ejecta near its outer boundary. (Bottom – F) The fastest jet particles have cleared the end of the polar ejecta.

and the maximum velocity of the particles in the jet,  $\beta$ . First the UV flash hits the beginning of the polar ejecta at day 7.8:

$$d(1 - \cos\theta) = ct_0 == 7.8 \text{ lt-d}, \quad (2)$$





**Fig. 6.** The U, B, V, R, and I points from the CTIO 0.41-m from days 6 to 50 (see Sect. 2).

where  $d$  is the distance to the beginning of the polar ejecta,  $\theta$  is the angle from the line of sight to the Earth to the beam/jet/polar ejecta direction, and  $c$  is the speed of light.

From Fig. 3 we also have the jet particles well into the polar ejecta by day 9.8. Extrapolating backward per above, we have the fastest beam particles hitting the polar ejecta at day 8.26:

$$d(1/\beta - \cos\theta) = ct_1 == 8.26 \ell t - d. \quad (3)$$

Next, we have the projected offset of 0.060 arc s for the Mystery Spot, measured at day 29.8 by Nisenson et al. (1987) and refined by Nisenson and Papaliolios (1999). This is more difficult to pin down relative to its position radially through the polar ejecta, so we assume it's some fraction,  $\alpha$ , of the way through the polar ejecta depth,  $D$ , and hope for a self-consistent solution:

$$(d + \alpha D) \sin\theta = ct_2 == 17.3 \ell t - d, \quad (4)$$

using 50 kpc for the distance to SN 1987A. Finally, we have the decrement in the light curve at day 20, shown in Fig. 3, which we will interpret as the fastest “substantial” bunch of particles in the jet breaking through the end of the polar ejecta:

$$(d + D)(1/\beta - \cos\theta) = ct_3 == 20 \ell t - d. \quad (5)$$

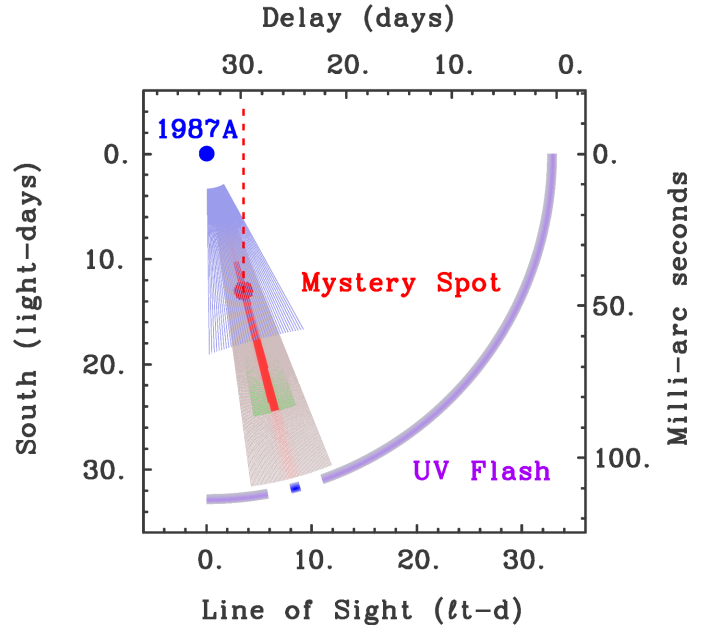
The solution to Eqns. 1-4 gives a constant ratio for  $D$  to  $d$ , independent of  $\alpha$ :

$$d = Dt_1/(t_3 - t_1), \text{ or } (d + D) = d t_3/t_1, \quad (6)$$

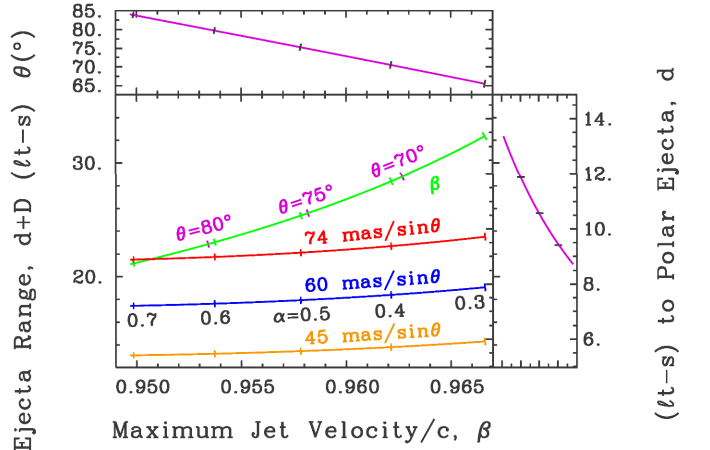
while  $\theta$  is given by:

$$\theta = 2 \tan^{-1} \left\{ \frac{t_0}{t_2} \left( \alpha \left( \frac{t_3}{t_1} - 1 \right) + 1 \right) \right\}. \quad (7)$$

The parameters,  $d$ ,  $D + d$ , and  $\theta$  are plotted against  $\beta$  in Fig. 8 for  $0.3 \leq \alpha \leq 0.7$ , along with the maximum  $d$  and minimum  $D + d$  implied by the three measurements of the Mystery Spot angular separation at days 30, 38, and 50. Figure 8 shows that the polar ejecta, at the very least, must start by 14  $\ell t$ -d or closer, and extend to 22  $\ell t$ -d or farther, consistent with our early 10  $\ell t$ -d estimates for  $d$  and  $D$ , as is the high value of  $\theta$  ( $65^\circ < \theta < 85^\circ$ ), which also means that the axis of bipolarity is  $\sim 30^\circ$  from the normal to the ring planes (Sugerman et al. 2005).



**Fig. 7.** The relation of the Mystery Spot, near day 30, to a jet, a thinning shroud, and a UV Flash, when its offset from SN 1987A was 0.045 arc s.



**Fig. 8.** The solution values for Eqns. 1-4, (Big frame horizontal) The maximum jet velocity,  $\beta$ . (Left vertical) The maximum range of the polar ejecta. (Right vertical axis) The distance from the pulsar to the beginning of the polar ejecta. The line with the steepest slope matches  $\beta$  (bottom) to  $D + d$  (left), or  $d$  (right), and three values for  $\theta$  are marked. The three other lines with moderate slopes constrain the minimum of  $D + d$  (right end of 74 mas curve), and the maximum of  $d$  (left end of the 45 mas curve and also read on the left vertical axis) from offset measurements of the Mystery Spot, which is assumed to be a jet-driven plume within the polar ejecta. (Top frame) Theta as a function of beta. (Right frame) Theta (horizontal axis identical to top frame vertical axis) versus  $D + d$  (left vertical), or  $d$  (right vertical).

Given the similar magnitudes of the early lightcurve and the Mystery Spot (and indeed, the two are just phases of the same phenomenon), the energetics are the same as posited in Meikle et al. (1987), except that the early lightcurve phase is shorter. For an interval of  $10^6$  s, at  $5 \times 10^{40}$  ergs  $s^{-1}$ , the optical output, mostly from reprocessing of higher energy photons resulting from the

jet particles scattering with electrons, is  $5 \times 10^{46}$  ergs. Since only a fraction of the particles scatter in the polar ejecta, the overall efficiency, in the conversion of kinetic energy into optical luminosity, could still be as low as Meikle et al.'s estimated 0.001, which gives  $5 \times 10^{49}$  ergs of kinetic energy in the initial jet. For 0.9 c protons, each with 0.002 ergs of kinetic energy, this would mean  $2.5 \times 10^{52}$  protons or  $2 \times 10^{-5} M_{\odot}$  initially each jet. Without the now visible counterjet, the “kick” velocity to the neutron star would be  $10 \text{ km s}^{-1}$ . For a pulsar with an initial spin rate of 500 Hz this short phase alone would result in a drop of 10 Hz, corresponding to a mean spindown rate of  $10^{-5} \text{ Hz s}^{-1}$ , assuming a neutron star moment of inertia of  $5 \times 10^{44} \text{ gm-cm}^2$ .

This may still be an underestimate, as accelerating a square  $\ell t$ -d of the polar ejecta column, which amounts to  $\sim 0.002 M_{\odot}$ , to  $\sim 0.3 \text{ c}$ , requires  $1.6 \times 10^{50}$  ergs of kinetic energy, which amounts to 6.6% of the  $2.5 \times 10^{51}$  ergs of rotational energy of a 500 Hz pulsar for each jet, or  $\sim 66 \text{ Hz}$  of frequency drop from 500 Hz, still assuming 100% conversion of jet kinetic energy into Mystery Spot kinetic energy, unless the plume has a smaller cross section than  $1 \ell t$ -d<sup>2</sup>, and/or the polar ejecta is less dense, on average, than  $10^7$ . Observations of initial pulsar spindowns (see Sect. 4) would help greatly in resolving this uncertainty. Spinup from accretion may temper the spindown somewhat (Patruno et al. 2009), but gravitational radiation reaction may counter it (Owen et al. 1998), though the high electromagnetic spindown will mask any effect of this latter on the pulsar braking index,  $n$ , where  $\frac{\partial f}{\partial t} \propto -f^n$ , and  $n = 5$  for pure gravitational radiation.

In either case, the rotational energy required is too large to be supplied by a strongly magnetized pulsar over the required timescale, unless these are born spinning faster than the moderate rates generally believed to be typical (e.g., the 16.1 ms PSR J0537-6910 – Middleditch et al. 2006). There was certainly no evidence for a strongly magnetized pulsar within SN 1987A in its first few years (e.g., Pennypacker et al. 1989; Ögelmann et al. 1990; Kristian et al. 1991), and most importantly, there is no evidence for such a pulsar in the last few years (NASA et al. 2003), whereas SN 1986J, at the same age, showed clear evidence of such a pulsar within it.<sup>2</sup>

However, there may be a weakly magnetized pulsar within SN 1987A (M00a,b), and at the very least this is supported by solid evidence for the formation of a neutron star (Bionta et al. 1987; Hirata et al. 1987). A binary merger of two electron-degenerate stellar cores (DD – in isolation these would be white dwarfs) has been proposed for SN 1987A (Podsiadlowski & Joss 1989), and the triple ring structure, particularly that of the outer rings, has recently been successfully calculated within this framework (Morris & Podsiadlowski 2007). Many other details of 87A, including the mixing (Fransson et al. 1989), the blue supergiant progenitor (Sanduleak 1969), the early polarization (Schwarz & Mundt 1987; Cropper et al. 1988; Barrett 1988), and the possible 2.14 ms optical pulsations (M00a,b), support this hypothesis.

The first clear evidence for DD-formed millisecond pulsars coincidentally came in the birth year of SN 1987A, with

<sup>2</sup> This SN, in the edge-on spiral galaxy, NGC 0891, exceeds the luminosity of the Crab nebula at 15 GHz by a factor of 200 (Bietenholz et al. 2004), and thus is thought to have occurred because of a core collapse due to iron photodissociation catastrophe (FeSN), producing a *strongly* magnetized neutron star ( $\sim 10^{12} \text{ G}$  – the origin of magnetic fields in neutron stars is still poorly understood, though it is believed that thermonuclear combustion in a massive progenitor to an Fe core is related).

the discovery of the 3 ms pulsar, B1821-24 (Lyne et al. 1987), in the non-core-collapsed globular cluster M28. Subsequently many more were found over the next 20 years in such clusters (e.g., 47 Tuc – Camilo et al. 2000), and attributing these to recycling through X-ray binaries has never really worked (Chen et al. 1993), by a few orders of magnitude.<sup>3</sup> Thus the DD process in SN 1987A, albeit within a common envelope, would likely have formed a rapidly spinning, weakly magnetized pulsar.

Consequently, we also argue, as a corollary implication useful for understanding the SN process and its modern-day observation history, that 99% of core-collapse events are similar to SN 1987A, in that they are a result of the double-degenerate process, producing only weakly magnetized, rapidly-spinning, millisecond pulsars, the notable exceptions being SN 1986J and SN 2006gy, this latter which will be discussed further below.

#### 4. The SN 1987A link to GRBs

Without the H and He in the envelope of the progenitor of 1987A (or perhaps even with it), Sk -69°202, the collision of the jet with the 1987A polar ejecta (which produced the early light curve and Mystery Spot) might be indistinguishable from a full  $\ell$ GRB (Cen 1999).<sup>4</sup> This realization, together with the observation that no  $\ell$ GRBs have been found in elliptical galaxies, and the realization that the DD process *must* dominate (as always, through binary-binary collisions), by a large factor the neutron star-neutron star mergers in these populations, even when requiring enough white dwarf-white dwarf merged mass to produce core-collapse, leads to the unavoidable conclusion that the DD process produces sGRBs in the absence of common envelope and polar ejecta, the means by which they would otherwise become  $\ell$ GRBs. Given that the sGRBs in ellipticals are due to mergers of white dwarfs, we can conclude that: 1) the pre-common envelope/polar ejecta impact photon spectrum of  $\ell$ GRBs is well characterized, 2) sGRBs are offset from the centers of their elliptical hosts because they are white dwarf-white dwarf mergers in their hosts' globular clusters (to produce most of their millisecond pulsars – Gehrels et al. 2005), and 3) neutron star-neutron star mergers may not make GRBs as we know them, and/or be as common as previously thought.<sup>5</sup>

Thus Supernova 1987A, with its beam and jet producing its early light curve and MS, is potentially the Rosetta Stone for three of the four types of GRBs,  $\ell$ , i, and s GRBs

<sup>3</sup> Relatively slowly rotating, recycled pulsars weighing  $1.7 M_{\odot}$ , in the core-collapsed globular cluster, Ter 5 (Ransom et al. 2005), have removed high accretion rate from contention as an alternative mechanism to produce the millisecond pulsars in the non-core-collapsed globular clusters. The three millisecond pulsars in Ter 5 with periods  $< 2 \text{ ms}$ , Ter 5 O, P, and ad (Hessels et al. 2006), may have been recycled starting with periods near 2 ms. There are four in this sample with periods between 2.05 and 2.24 ms, and perhaps most importantly, the first from Arecibo ALFA, 1903+0327 (Champion et al. 2008), at 2.15 ms very close to the candidate 2.14 ms signature of SN 1987A (M00a,b), with a main-sequence companion, from which it could never have accreted mass, nor significantly from any other source, because of its own modest mass.

<sup>4</sup> Otherwise it would just beg the question of what distant, on-axis such objects would look like.

<sup>5</sup> Thus sGRBs may not flag neutron star-neutron star mergers, which may last only a few ms, the same timescale as the 30-Jy, DM=375 radio burst (Lorimer et al. 2007), far shorter than sGRBs (Hansen & Lyutikov 2001).

(Horváth et al. 2006),<sup>6</sup> with both polar ejecta and common envelope, red supergiant common envelope and no polar ejecta, and neither polar ejecta nor common envelope, respectively (Middleditch 2007 – hereafter M07).

In addition to axially driven pulsations, the SLIP model makes the very unique and remarkable prediction that the component of pulsar intensity which obeys Eqn. 1, diminishes only as distance<sup>-1</sup>, and this has been verified experimentally (Ardavan et al. 2004), and also appears to be holding up (Singleton et al. 2009), for pulsars in the Parkes Multibeam Survey (e.g., Lorimer et al. 2006). There is also evidence that GRB afterglows share this characteristic (Kann & Klose 2008), which supports the SLIP prediction of axially driven pulsations when plasma is available at many  $R_{LC}$ . The SLIP prediction is convenient also because it explains how afterglows (and GRBs) can be visible across the Universe.<sup>7</sup> As a consequence of this prediction, we have initiated a campaign of high speed monitoring of GRB afterglows.

If, as for SN 1987A, 99% of SNe are DD-initiated, then by measuring the pulse period,  $P$ , of the optical/near infrared pulsations from an afterglow, and assuming the pulsars resulting from DD are all produced at a standard spin period,  $P_0$ , first measured from SN 1987A near 2.14 ms, the redshift is given by:

$$z = \frac{P}{P_0} - 1, \quad (8)$$

and even a moderately precise  $P$  (by standards), may yield a very precise redshift.

In the SLIP model, the peak of the emission for slowest pulsars occurs in the gamma-ray band (Ardavan et al. 2003,9), and this is supported by recent gamma-ray detections of slow ( $\sim 1$  Hz) pulsars in supernova remnants by FERMI (e.g., Abdo et al. 2008). There is no requirement in the SLIP model on the rotator being a neutron star – a white dwarf will do as long as it has a magnetic field and there is plasma outside of its light cylinder. If this is the case, strongly magnetized pulsars may not make GRBs, and it might even be possible for a pre-core-collapse,  $\sim 1.4 M_\odot$  white dwarf, spinning at its minimum period of 1.98 s, to emit the prompt part of a GRB, and, as with the afterglow, the distance<sup>-1</sup> law would likewise ameliorate the energy requirement, even with the large expected spinup. This also raises the intriguing possibility that a GRB could be produced without core-collapse, and a large spin-down may be present. We tested for spinup/down in the GRB with the highest fluence in the BATSE catalog, 960216 (Paciesas et al. 1999), by Fourier transforming the first 40 s of events and contouring power on the frequency- $\frac{\partial f}{\partial t}$  plane. Power appears, though not significant without further confirmation, at a mean frequency of 0.50 Hz, and derivative of  $+0.08 \text{ Hz s}^{-1}$ , and also for spinup/down about an order of magnitude smaller, in the 0.35 to 0.42 Hz region. Bursts with even better statistics (perhaps from FERMI) may be necessary to further test this hypothesis.

The geometric model with small angle scattering of gamma-rays in distant polar ejecta can explain other details of  $\ell$ GRBs, such as their  $\sim 100 \text{ s } T_{90}$ 's,<sup>8</sup> the negligible spectral lag for late ( $\sim 10$ – $100 \text{ s}$ ) emission from “spikelike” bursts (Norris & Bonnell 2006), and why “precursor” and “delayed”

contributions have similar temporal structure (Nakar & Piran 2002; M07).

## 5. Double-Degenerate in Type Ia/c SNe

Since 2007, Feb., it appeared unavoidable that Type Ia SNe were also DD-caused, one of the causes being the long list of reasons why Ia's can not be due to thermonuclear disruption (M07). Now it is not clear if this ever happens in *any* progenitor (see, e.g., Seigfried 2007), and empty SN remnants almost always contain a neutron star which is just not visible, just as the one in Cas A is barely visible (Tananbaum et al. 1999). Further, this means that Ia's and Ic's (these latter have been regarded by many as DD-initiated, neutron star-producing since the invention of the classification), are both due to the DD process, and thus must form a continuous class: Ia's when viewed from the merger equator, with lines of Fe; and Ic's when viewed from the merger poles, because this view reveals lines of the r-process elements characteristic of Ic's,<sup>9</sup> part of the reason for the differing spectroscopic classification. The high approaching velocities frequently seen in Ic's (e.g., “hypernovae”) are due to the view looking down the axis of the approaching bipolarity.

In the application of Type Ia SN luminosities for cosmological purposes, the increase in blue magnitude from the light curve maximum,  $\Delta M_B$  (essentially an inverse measure of the width of the light curve in time), measured in the first few weeks of SN Ia proper time, is used to correct the Ia luminosity for the variable amount of  $^{56}\text{Ni}$  produced (Phillips 1993). However, the direct relation, between the  $\Delta M_B$  of the width-luminosity relation and the fractional SiII polarization in Ia's, pointed out by Wang et al. (2006), is more meaningfully interpreted as an *inverse* relation between the SiII polarization and luminosity (unlike the Fe lines, SiII lines must also exist in the axial features because they are also observed in Ic's, and their polarization in Ia's is a result of the more rapid axial extension when viewed close to the merger equator). This inverse relation would be expected in Ia's if the luminosity of the axial features were fixed, while the luminosity of the toroidal component is driven by the amount of encapsulated  $^{56}\text{Ni}$  positron annihilation gamma-rays, which can be very high.<sup>10</sup>

Because there is a spectroscopic difference between Ia's and Ic's, the SLIP-driven polar jets are either deficient in  $^{56}\text{Ni}$ , or are too diffuse to encapsulate their gamma-rays, or both. *No* observation of *any* recent SN other than SN 1986J and SN 2006gy, including all *ever* made of Type Ia SNe, is inconsistent with the bipolar geometry of 1987A.

All this raises serious concerns about the use of SNe Ia in cosmology, because many Ia/c's in actively star-forming galaxies belong to the continuous class, and some of these, and most Ia's in ellipticals, may not encapsulate a sufficient fraction of their gamma-rays to be bolometric (Pinto & Eastman 2001), especially given the toroidal geometry, lying as much as two whole

<sup>9</sup> If sufficient matter exists, in excess of that lost to core-collapse, to screen the Ia thermonuclear products – a rare circumstance in elliptical galaxies, the reason why Ic's are absent from these.

<sup>10</sup> As with 1987A-like events, it would again beg the question of “What *else* they could possibly be?” and “delayed detonation” (Khokhlov 1991), or “gravitationally confined detonation” (Plewa et al. 2004), do not produce polarization which would be inversely proportional to luminosity. And unless the view is very near polar, this geometry can produce split emission line(s) on rare occasions, as was seen in SN 2003jd (Mazzali et al. 2005), and thus again there is no need to invoke exotica, or an entire population (III) to account for GRBs (Conselice et al. 2005; M04).

<sup>6</sup> All except Soft Gamma Repeater (SGR) GRBs, which are estimated to amount to less than 5% of sGRBs and 1.5% of the total (Palmer et al. 2005).

<sup>7</sup> In the case of SN 1987A, the pulsations may have had to be observed through  $\sim 13 \ell$ -d of polar ejecta.

<sup>8</sup> An offset of  $0.5^\circ$  at  $\sim 10 \ell$ -d corresponds to a 33 s delay.

magnitudes below the width-luminosity relation (the faint SNe Ia of Benetti et al. 2005). In the SLIP model the pulsar eviscerates its stellar remnant as long as there is remnant remaining, enforcing a toroidal geometry of ejecta near its rotation equator. Even if this toroid is very much brighter than the axial jets, as is the case in many Ia/c's, the *opacity* of the axial jets, in front of rear sections of the toroid, which would otherwise be visible even for small inclinations away from  $90^\circ$  (a viewing angle for which essentially all SNe Ia/c will be classified as Ia's), may change during the interval when the width-luminosity relation is measured, literally and figuratively casting a shadow of reasonable doubt over attempts to use Ia/c's as cosmological standard candles.

## 6. Type II SNe and Other Details

The double-degenerate mechanism ensures that nearly all SNe are born from a post-merger white dwarf with a rotation period near 1.98 s, thus rapid rotation can not be invoked as an unusual circumstance, for the case of SN 2003fg, to justify “super-Chandrasekhar-mass” white dwarfs. The  $>1.2 M_\odot$  of  $^{56}\text{Ni}$  it produced may only mean that core collapse underneath mixed thermonuclear fuel can initiate very efficient combustion/detonation,<sup>11</sup> the paltry amounts of  $^{56}\text{Ni}$  associated with Ib's and at least 90% of IIs being the result of dilution of their thermonuclear fuel with He and/or H due to the DD merger process.<sup>12</sup> Thus SN 2006gy (Smith et al. 2007) may not be a pair-instability SN (Woosley et al. 2007; Kawabata et al. 2009), or a collision of two massive stars (Portegies Zwart & van den Heuvel 2007),<sup>13</sup> only a massive FeSN of up to  $75 M_\odot$ , which may actually have produced several  $M_\odot$  of  $^{56}\text{Ni}$ , and a strongly magnetized neutron star remnant, a prediction which can be tested soon.<sup>14</sup>

The presence of plasma makes a huge difference to rapidly rotating, weakly magnetized neutron stars. Strong pulsations have occurred during observations of SN remnants or X-ray binaries which have never been subsequently confirmed, and yet have no explanation other than as a real, astrophysical source (e.g., Bleach et al. 1975). Judging from the high fraction of empty SN remnants, the population of “quiet” neutron stars (Weatherall 1994) must exceed all other “loud” populations combined. Only when such a weakly-magnetized, rapidly-spinning neutron star encounters a cloud of matter will it become sufficiently luminous to be detected. In the context of the SLIP model, radiation from the known millisecond pulsars may very well be detected from Earth because we are “in the cusp,” i.e., we are in the part of the pulsar's beam (Eqn. 1) that decays inversely only as the first power of distance. If this is not the case, young neutron stars may only appear as thermal sources, such as the one in Cas A (Tananbaum et al. 1999). A century older,

as is the case with Tycho 1572, or more deeply embedded in the Galactic plane, as is the case for Kepler, 1604, and not even the thermal sources are detectable. Evidence does linger, however, at least in the outwardly very spheroidal remnant of SN 1006, as bipolar high energy emission in XMM and VLA images (Rothenflug et al. 2004).

In the case of SN 1987A, plasma initially available at many  $R_{LC}$  resulted in axially driven pulsations. As the circum-neutron star density declined, polarization currents were restricted to fewer  $R_{LC}$ , resulting in pulsed emission along a cone of finite polar angle, which may have modified the resulting beam/jet into the approaching and retreating conical features now easily visible in the HST ACS images (NASA et al. 2003). Eventually, as the plasma continued to thin with time, its maximum density occurred between  $2R_{LC}$  and just outside of  $R_{LC}$ , resulting in pulsations driven close the pulsar's rotational equator, and according to our self-consistent solution, in the line of sight to the Earth. Precession and nutation may have further embellished the axial pattern (M00a). Even if totally absorbed, such a beam would produce an observable excess luminosity that may have been seen by 1991 (Cowan 1991; Suntzeff et al. 1991,2), as the amount of  $^{57}\text{Co}$  required to otherwise account for the excess was only barely consistent with hard X-ray and infrared spectral data (Kumagai et al. 1989; Rank et al. 1988). A few years earlier it is unlikely that the 2.14 ms signal would have been detectable in the broadband, as limits established in early 1988 (Pennypacker et al. 1989) are comparable to levels of the 2.14 ms signal observed in the I band between 1992, Feb. and 1993, Feb. The 2.14 ms pulsar candidate was last detected in 1996, Feb. (M00b), and by 2002 there was no evidence of any such source in ACS images, which only really means that any pulsar within SN 1987A had entered the “Cas A” phase,<sup>15</sup> having exhausted its surrounding plasma supply and perhaps also because the Earth was no longer in the “cusp” of its beam(s). Still, the central source should turn on when the pulsar encounters matter from time to time.

A beam of protons, with kinetic energies of up to 2.2 GeV or greater, will eventually produce electrons with similar energies. Even higher energies may result from core-collapse events with less material in the common envelope, and/or these may, in turn, be further accelerated by magnetic reconnection, in wound-up magnetic fields near the Galactic center, or other mechanisms (Schure et al. 2009), possibly to TeV energies, to produce the WMAP “haze” observed in that direction (Finkbeiner 2004). In addition, the loss of positrons, which occurs because of the bipolarity of SNe, which also makes them unfit for easy cosmological interpretation, may show up as an excess in cosmic ray data (Chang et al. 2008; Abdo et al. 2009; Adriani et al. 2009), a satisfying resolution for the apparent anomalous dimming of distant SNe explained in terms of local cosmic ray abundances.

<sup>11</sup> The spectroscopic demands of a significant mass of unburned fuel, such as O, being invalid because of the invalid paradigm under which such estimates were made.

<sup>12</sup> Helium has been found where it was not expected in almost all well-studied SNe.

<sup>13</sup> The inner layers of all FeSNe, possibly *many*  $M_\odot$  of Si, Ne, O, and C, have not been diluted with He by DD, and thus may ignite/detonate upon core collapse, and burn efficiently. SN modelers therefore face the unenviable choice of calculating FeSNe, which involve strong magnetic fields, or DD SNe, which involve a great deal of angular momentum, and *demand* GRBs as an outcome (see Sect. 4).

<sup>14</sup> As a corollary,  $40 M_\odot$  in a SN remnant is no longer a reason to invoke “millisecond magnetars,” as the dispersal mechanism (Thompson et al. 2004; Vink & Kuiper 2006)

<sup>15</sup> Calculations with the SLIP model involve a variation of Kepler's equation, which relates the eccentric anomaly,  $E$ , to the mean anomaly,  $M$ , using the eccentricity,  $\epsilon$ ,  $E - \epsilon \sin E = M$ , but in this case  $\epsilon > 1$ . Such calculations are notoriously difficult, even for a compact star *not* surrounded by remnant plasma. Needless to say, no such calculations have been done to date, and thus no calculation done so far, including those of “collapsars,” can possibly be valid. One side effect of not properly accounting for the pulsar, and the large amount of  $^{56}\text{Ni}$  when strongly-magnetized pulsars are produced, is a very low estimate for the mass,  $\sim 25 M_\odot$ , above which the core collapse continues on to a black hole. SN 2006gy, with several  $M_\odot$  of  $^{56}\text{Ni}$ , exposed this delusion.



## 7. Conclusion

We have derived a self-consistent solution for the onset ( $\sim 11 \ell t$ -d), and depth ( $\sim 13 \ell t$ -d), of the polar ejecta of the progenitor of SN 1987A, the energetics of its beam/enhanced UV flash, the kinetics of its jet, and angle from the line of sight to the Earth ( $\sim 75^\circ$ ). There is plenty of evidence for the absence of any strongly magnetized pulsar within SN 1987A, and such a pulsar may not have the rotational energy to account for the kinetics anyway. Thus, we have argued, through the paradigm of a model of pulsar emission from superluminally induced polarization currents (SLIP) which uses emission from polarization currents induced beyond the pulsar light cylinder (Ardavan 1998), that SN 1987A, its beam/jet, “Mystery Spot,” and possible 2.14 ms pulsar remnant, are intimately related to as many as 99% of GRBs, millisecond pulsars, and other SNe, including all Type Ia SNe. The SLIP model explains, in a natural way (Eqn. 1), the changes over time observed in the collimation of the SN 1987A beam and jet.

The time lags, energetics, and collimation of  $\ell$ GRBs are consistent with those of 1987A’s beam, jet, and “Mystery Spot”. When the bipolarity of SN 1987A is interpreted through this model, its pulsar clearly had ablated the  $\sim 10 M_\odot$  of ejecta, eviscerating the remnant by blowing matter out of its poles at speeds up to 0.95 c or greater, and enforcing a toroidal geometry on the remaining equatorial ejecta. Since there is no reason to suggest that this is not universally applicable to all SNe, this geometry has grave implications for the use of Type Ia SNe as standard candles in cosmology.

The interaction of even a weakly magnetized pulsar with the rest of the remnant of the progenitor (if this rest exists), clearly can not be ignored. There appears to be no need to invent exotica to explain GRBs – the SLIP model provides the young pulsar (or even a near-Chandrasekhar-mass white dwarf) as the central engine, and makes the very specific and testable prediction that GRB afterglows are, in fact, pulsars. In addition, because of the unsuitability of SN geometries for cosmological interpretation, the expansion of the Universe may not be accelerating, and, as a consequence, there may be no dark energy. But if there is no dark energy, then there is no numerical coincidence to support the role of dark matter in Concordance Cosmology. Recent observations have also cast significant doubt on the existence of dark matter (Nelson & Petrillo 2007; Madore et al. 2009).

Although it might appear that a Universe without dark matter or energy, collapsars, pair instability SNe, super-Chandrasekhar mass white dwarfs, frequent collisions of massive stars, and neutron star-neutron star mergers which make sGRBs, is much less “exotic” than previously thought, pulsars, i.e., clocks and minutes-old neutron stars to boot, which can be seen across almost the entire Universe, may well suffice in explaining all of the issues which gave rise to the previously mentioned entities, are more in line with Occam’s Razor, and are also, of themselves, extremely worthy of study.

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